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STUDY ON MICRO VALVE USING MICRO FLUIDIC DEVICE AND ZERO-NET-FLOW-RATE MICRO JET

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ABSTRACT

Characteristics of a mini/micro-size Y-type fluidic device were examined using water as test fluid. The cross-section of an inlet path and outlet branches was 1 mm × 1 mm square. That of signal ports was 1 mm × 0.5 mm. Although Reynolds number tested was low; less than 1000, the mini/micro-size fluidic device functioned as the fluidic device; flow provided for a signal port flowed out from an opposite outlet. It was also analytically proved by the commercial code of STAR-CD. A zero-net flow micro-jet which had been analytically predicted was experimentally confirmed. A piezoelectric element was used to produce the zero-net flow micro-jet. A new concept of the mini/micro-size fluidic device was proposed. In that design, the signal ports were replaced with the zero-net flow micro-jet which was formed by the piezoelectric element. It was confirmed that the new design would function as the fluidic device.

INTRODUCTION

Micro-machine technology has been studied by many investigators actively for recent several decades. It has been proved that the technology is really innovative since it has the possibility to provide an advanced and a new world for mechanical engineering. Further progress is undoubtedly required in order to incorporate the outcome of micro-machine technology researches into real-advanced machines. Physics in the micro-scale such as thermal-hydraulics, material characteristics, mechanical dynamics and so on has to be elucidated.

When the size of the flow channel is scaled down, the ratio of surface area to volume increases and frictional pressure loss increases drastically. In that condition, it often becomes difficult and important to control a flow rate in the system. Rotating or moving parts should be evaded in the micro-mini systems.

Fluidic devices have been examined in the past by many investigators. The theory and the standards for designing are found in many textbooks, for example Ozaki et al. (1967). The fluidic device can control the flow rate and switch the flow direction without any moving and rotating parts. Thus, if it is incorporated into micro-mini systems, it may come out one of the most valuable parts of micro-mini systems.

Miwa et al. (2003) investigated a micro jet. The bottom of a box which had a small opening at the top was vibrated at a high frequency. A jet flow from the opening was created out side of the box without a time-averaged net flow at the opening.

If the fluidic device and the zero net-flow micro-jet were combined, that system would be a simple-reliable-durable component for flow controlling with great freedom. In the present paper, very simple mini/micro-size fluidic devices were manufactured and it was examined whether those could function as a flow control system. The zero net-flow micro-jet was also experimentally examined. Then, by combining the fluidic devices and the zero net-flow micro-jet, the new concept of the mini/micro-size fluidic device was proposed. It was confirmed that it could function as a flow control component. It was supported by the numerical simulation by the commercial code of STAR-CD.

EXPERIMENTAL APPARATUS AND PROCEDURES

Mini/Micro-Size Y-Type Fluidic Device

Apparatus

A test section used in the present experiments is exhibited in Fig. 1. A Y-type flow channel (groove) is formed on a transparent Plexiglas plate. Another transparent Plexiglas plate is placed on the grooved Plexiglas plate sandwiching a 0.1 mm thick silicone sheet. Two plates are fixed tightly by bolts. Between the grooved and the Plexiglas cover plate the Y-type test flow channel is formed. Both the cross-section of the bottom and branch part of Y are 1 mm × 1 mm. The flow channel has two signal ports at the crossing point of Y. Of course the signal ports are grooved initially on the Plexiglas plate surface before combining two plates. The cross-section of the signal ports is 0.5 mm × 1 mm. Three holes are formed in the cover plate as shown in Fig. 1 for fluid to come into the Y-shape flow channel. Two holes are also formed in the grooved plate for fluid to come out. In the present paper, the bottom and the top of Y are called Inlet 0, and Outlet A and Outlet B, respectively. The signal ports are called Inlet 1 and Inlet 2, respectively.

The test section is placed horizontally as shown in Fig. 2. Distilled water as test fluid is supplied to Inlet 0 of the test section through a rotameter and a valve from an open head-tank that is placed at 1.5 m above the test section. Flow pulsation was eliminated by adopting flow supply from the head tank. Water flowing out from Outlet A and Outlet B drips down to a catch tank that is open to the atmosphere. Signal flow is also provided for Inlet 1 or Inlet 2 through a rotameter and a valve from the head tank.

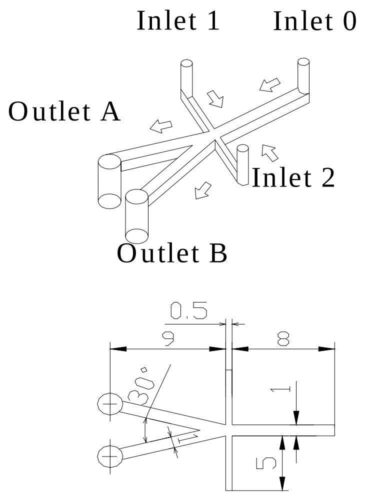


Fig.1 Test Section of Mini/Micro-Size Y-Type Fluidic Device

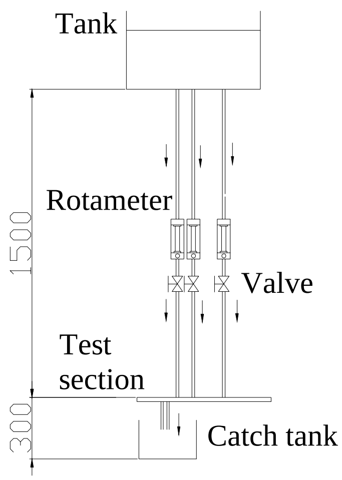


Fig. 2 Experimental Apparatus of Mini/Micro-Size Y-Type Fluidic Device

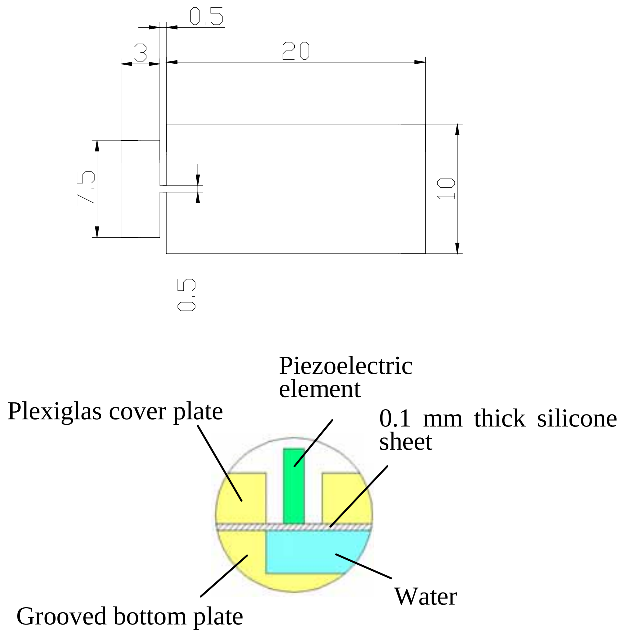


Fig. 3 Test Section for Visualization of Zero Net-Flow Micro-Jet

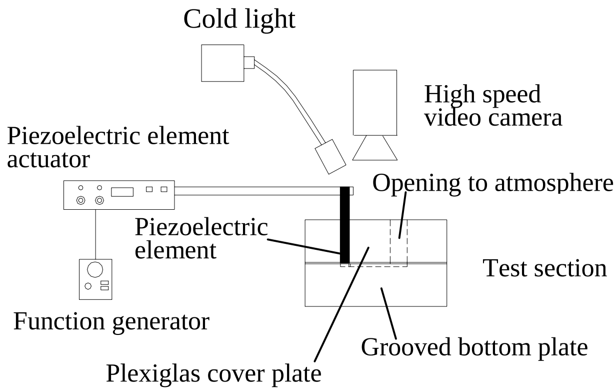


Fig. 4 Experimental Apparatus of Visualization of Zero Net-Flow Micro-Jet

Procedures

Flow rates from the head tank to Inlet 0, Inlet 1 and Inlet 2 are measured with rotameters. A flow rate from each outlet is measured by collecting water coming out from the outlet in a measuring cylinder for a certain time period. Uncertainty of the flow rates measured by the rotameters and the measuring cylinder is quite low; less than 1 %. Experiments are performed under atmospheric pressure and room temperature.

At the beginning of experiments, water was only provided for Inlet 0. Then, it was confirmed that flow was equally divided in the test device. After this confirmation, signal flow was supplied to Inlet 1 or Inlet 2 depending test conditions. The flow rates to Inlet 0 and Inlet 1 or Inlet 2 and also the flow rates from Outlet A and Outlet B were measured after the flow state was fully stabilized. Then, the flow rate to the signal ports was increased and the same procedure was iterated.

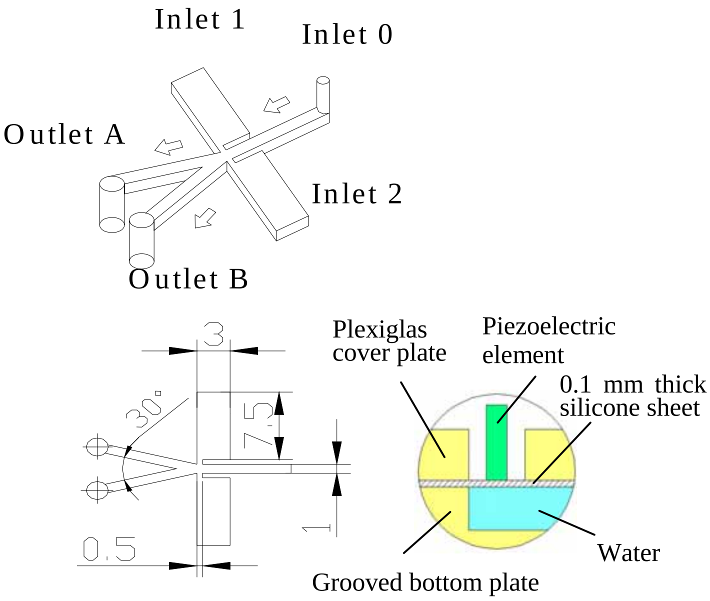


Fig. 5 Test Section for Integration of Mini/Micro-Size Y-Type Fluidic Device and Zero Net- Flow Micro-Jet

Visualization of Zero Net-Flow Micro-Jet

Apparatus

Two rectangles that are connected by a small neck are grooved on the transparent Plexiglas plate as shown in Fig. 3. Another transparent Plexiglas plate was placed on the grooved plate that was oriented horizontally sandwiching a 0.1 mm thick silicone sheet as shown in Fig. 3. The left rectangular box in Fig. 3 was a closed box that had only one outlet connecting to the right rectangular box. The right rectangular box had an opening to the atmosphere through a hole formed in the cover plate as shown in Fig. 4.

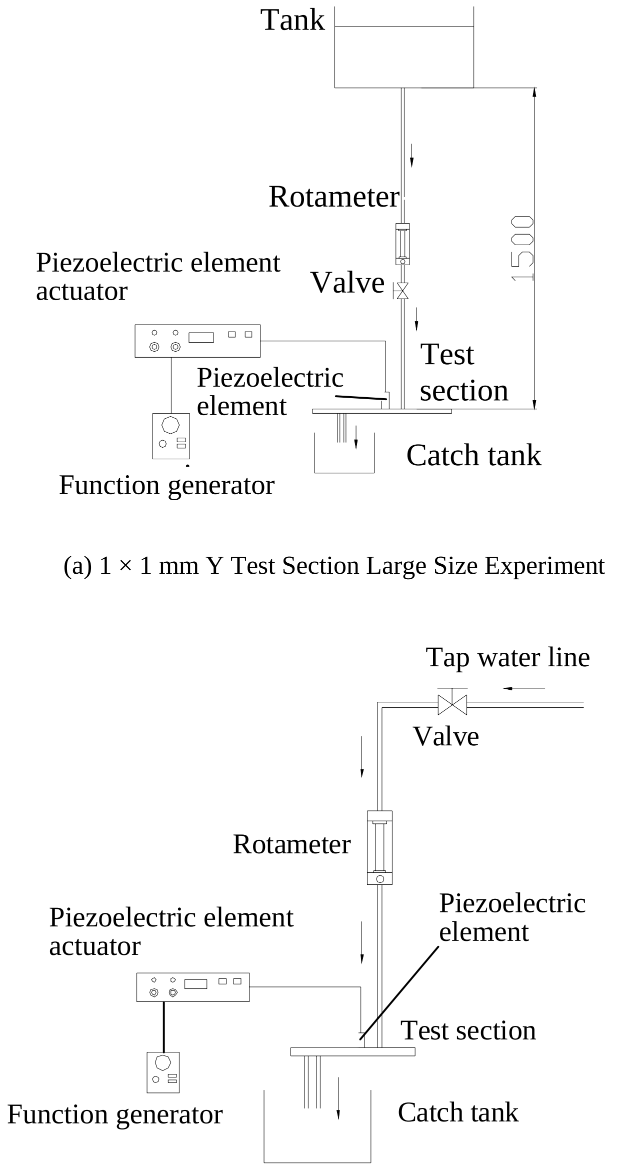
Two types of the neck part size of 0.5 × 1 mm and 0.2 × 0.2 mm were used in the present experiments.

A piezoelectric element was glued to the silicone sheet at the ceiling of the left box as shown in Fig. 3. The moving stroke of the piezoelectric element was 28 μm. The piezoelectric element was actuated by an amplifier and a function generator.

Procedures

The boxes were filled with distilled water. Tracer particles of 3 μm diameter were mixed in water in advance. The piezoelectric element was actuated, and then after a wile a flow state was recorded with a high speed video camera up to the frame rate of 120,000 flame/s.

Integration of Mini/Micro-Size Y-Type Fluidic Device and Zero Net- Flow Micro-Jet



(a) 1 × 1 mm Y Test Section Large Size Experiment

(b) 0.2 × 0.2 mm Test Section Small Size Experiment

Fig. 6 Test Apparatus of Integration of Mini/Micro-Size Y-Type Fluidic Device and Zero Net- Flow Micro-Jet

Apparatus

A test section used in the present experiments is illustrated in Fig. 5. A Y-type flow channel is formed in a transparent Plexiglas. The design is the same as that in Fig. 1. The differences from the apparatus shown in Fig. 1 are the signal ports. The backside of the signal port opening is connected to a dead-end box. A piezoelectric element was glued to the silicone sheet between the grooved bottom plate and the cover plate at the ceiling of the dead-end box as shown in Fig. 5. This design is the same as that shown in Fig. 3. The piezoelectric element used in experiments was the same as that used in the visualization experiments of the zero net-flow micro-jet.

Two types were tested. One was that both the cross-section of the bottom and the branch part of Y were 1 mm × 1 mm and the cross-section of the signal port opening to the flow channel was 0.5 mm × 1 mm. Other was that both the cross-section of the bottom and the branch part of Y were 0.2 mm × 0.2 mm and the cross-section of the signal port opening to the flow channel was 0.2 mm × 0.2 mm.

The test section is placed horizontally as shown in Fig. 6 (a) and (b). Distilled water as test fluid is supplied to Inlet 0 of the test section through a rotameter and a valve from an open head-tank at 1.5 m above the test section in the 1 mm × 1 mm cross-section experiments (Large Size Experiments, Fig. 6 (a)) as in the mini/micro-size Y type fluidic device experiments in Fig. 2. In the 0.2 mm × 0.2 mm cross-section experiments (Small Size Experiments, Fig. 6 (b)), water is supplied through a rotameter from a tap water line. Water flowing out from Outlet A and Outlet B drips down to a catch tank that is open to the atmosphere. A flow rate from each outlet is measured by collecting dripping water in a measuring cylinder for a certain time period.

Procedures

After it was confirmed that the flow provided for Inlet 0 was equally divided in the flow device as mentioned above, the piezoelectric element was actuated. After a wile, outlet flow rates from Outlet A and Outlet B were measured by collecting in measuring cylinders. Which piezoelectric element was actuated was depending on the test condition.

NUMERICAL ANALYSES BY STAR-CD CODE

The Y-type fluidic device of the 1 mm × 1 mm cross-section was modeled two-dimensionally and the flow behavior in it was analyzed by the commercial code of STAR-CD. In the simulation, a wall was non-slip, the high Reynolds number k – ε model was used, the turbulent intensity was 0.03, the vortex scale was 0.00001 m and the total cell number was 116,004.

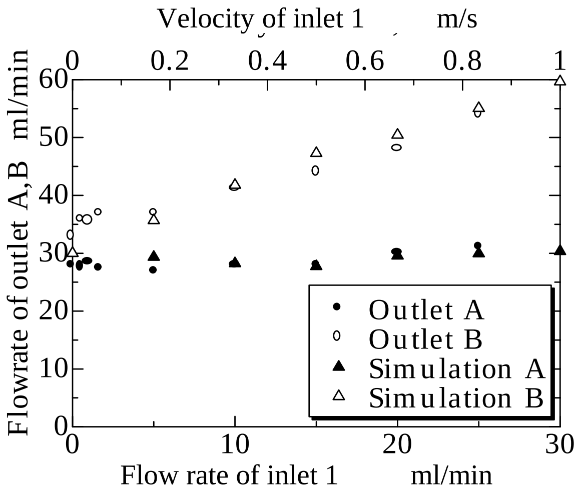


Fig. 7 Results of Mini/Micro-Size Y-Type Fluidic Device

EXPERIMENTAL RESULTS AND DISCUSSIONS

Results of Mini/Micro-Size Y-Type Fluidic Device

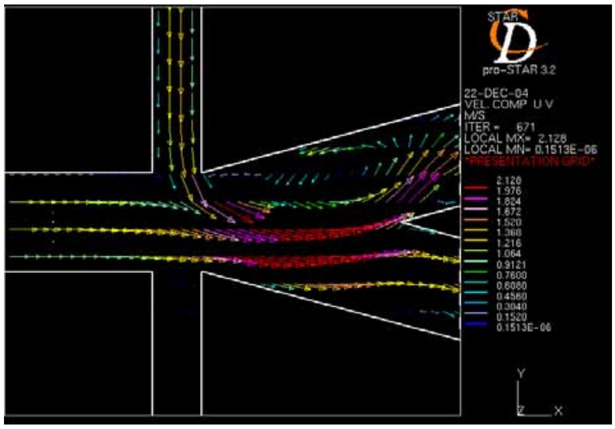


Fig. 8 Flow Field by STAR-CD Code

Measured outlet flow rates are plotted against the inlet flow rates of Inlet 1 in Fig. 7. The inlet flow to Inlet 0 was kept at 60 ml/min throughout the experiments. Signal flow was only provided for Inlet 1. In the figure, simulation results by the STAR-CD code for the same test conditions are also included for comparison.

In Fig. 7, the outlet flow rate from Outlet B is almost constant although the inlet flow rate to Inlet 1 is increased. On the contrary to this, the outlet flow rate from Outlet A increases as the inlet flow rate to Inlet 1 is increased. The flow provided for one signal port flows out from the opposite side outlet. The Reynolds number at the inlet (the bottom channel of Y) is approximately 1,000. It is confirmed that the Y-type fluidic device functions even at low Reynolds number.

The experimental results are well simulated by the STAR-CD code as shown in Fig. 7. The detailed flow field at the branching section is presented in Fig. 8. Some vortices exist in the nearest branch downstream. The vortices and the backward flow act like a valve for the signal port flow. Thus, the signal port flow goes to the opposite side branch.

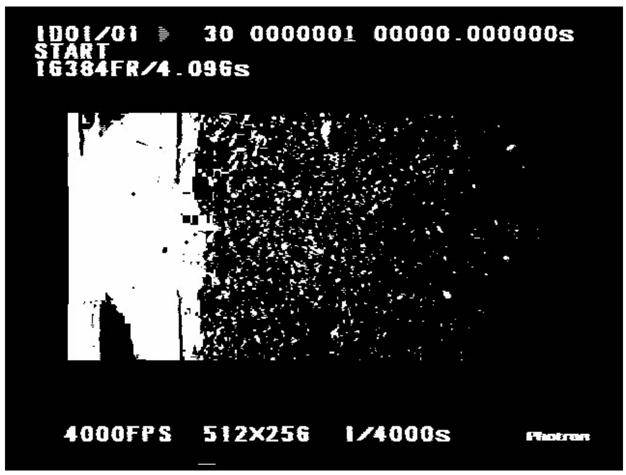


Fig. 9 Particle Image of Visualization Experiment of Zero Net-Flow Micro-Jet

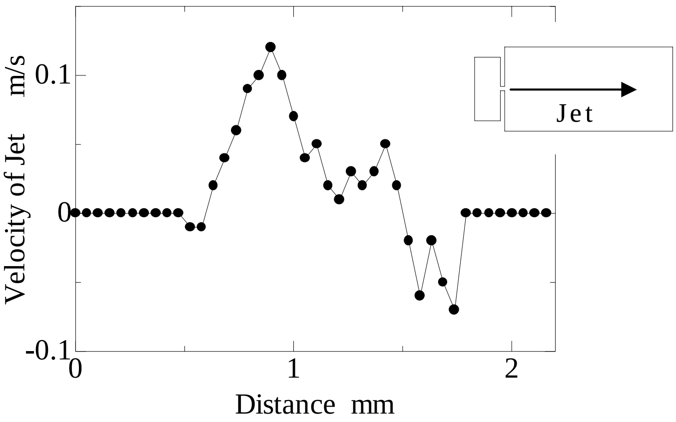


Fig. 10 Average Velocity of Zero Net-Flow Micro-Jet along Center Line

Results of Visualization of Zero Net-Flow Micro-Jet

One example of the image of particles captured by a high speed video camera is presented in Fig. 9. The case presented in the figure is that the neck size between the dead end box and the outside is 0.5 × 1.0 mm and the frequency of the piezoelectric element is 200 Hz. By using images like that presented in the figure, a PTV method was used to get a flow field. An obtained flow velocity is shown in Fig. 10. The velocity shown in the figure is the time-averaged velocity along the center of the neck downstream. The horizontal axis 0 is the outlet of the neck. The figure exhibits the existence of the net positive flow from the outlet to the outside. The positive flow area extends over 1.5 mm from the outlet.

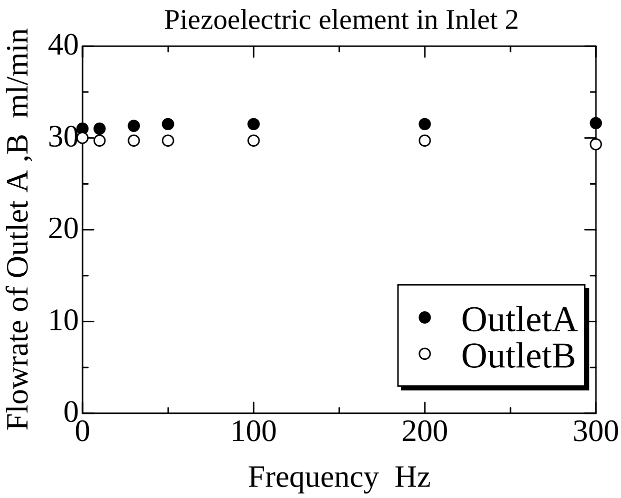


Fig. 11 Results of Integration of Mini/Micro-Size Y-Type Fluidic Device and Zero Net- Flow Micro-Jet (1 × 1 mm Cross-Section Test section)

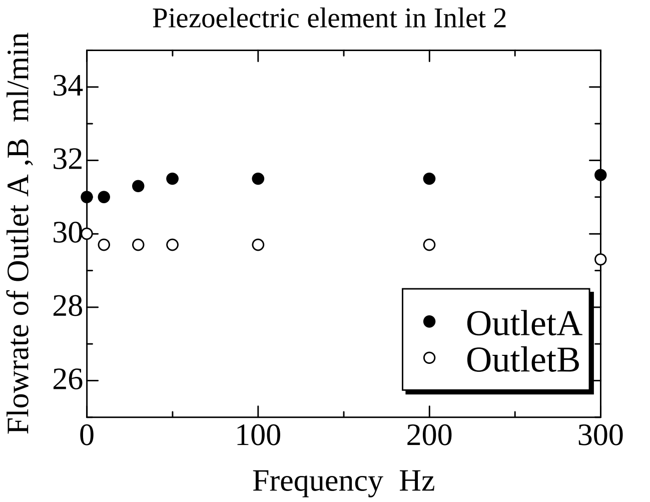


Fig. 12 Results of Integration of Mini/Micro-Size Y-Type Fluidic Device and Zero Net- Flow Micro-Jet (1 × 1 mm Cross-Section Test section)

Results of Integration of Mini/Micro-Size Y-Type Fluidic Device and Zero Net-Flow Micro-Jet

The measured outlet flow rates from Outlet A and Outlet B are presented in Fig. 11. The case shown in the figure is that the main flow channel of the Y-type flow device is 1 mm × 1 mm and the signal port opening to the flow channel is 0.5 mm × 1 mm (Large Size Experiment). A piezoelectric element in Inlet 2 was actuated. Although the effect is not prominent, some increase in the flow rate in the Outlet B; the opposite side of the Inlet 2, is observed as the frequency of the piezoelectric element is increased. As shown in Fig. 10, the order of the outlet flow velocity of the zero net-flow micro-jet is 0.1 m/s. The outlet neck size in the case shown in the figure is 0.5 mm × 1 mm and the piezoelectric element frequency is 200 Hz. If this velocity is applied to the results in Fig. 11, the velocity corresponds to the flow rate of 3 ml/min. It is too small compared with the main flow rate. In Fig. 12, the vertical axis is expanded. The increase in the flow rate from Outlet A is approximately 1 ml/min at 200 Hz. This order is close to the results in Fig. 10. It could be confirmed that the zero net-flow micro-jet could provide the role of the signal port flow for the micro-size Y-type fluidic device although the tested flow rate range was quite limited.

Figure 13 shows the results of the case of the small size experiments (0.2 mm × 0.2 mm cross-section, Small Size Experiment). Regrettably, it is hard to see the effect of the zero net-flow micro-jet on the signal port flow of the micro-size Y-type fluidic device. The outlet flow rate from Outlet A does not show an increase as the frequency of the piezoelectric element actuation is increased. The flow velocity of the zero net-flow micro-jet might be provably too small.

If it is succeeded in getting the high velocity of the back-and-force flow at the neck, the high velocity of the zero net-flow micro-jet may be attained. If so, it may be expected that the proposed system would work more prominently. At least it could be proved that the zero net-flow micro-jet functioned as the signal port flow in the micro-size Y-type fluidic device.

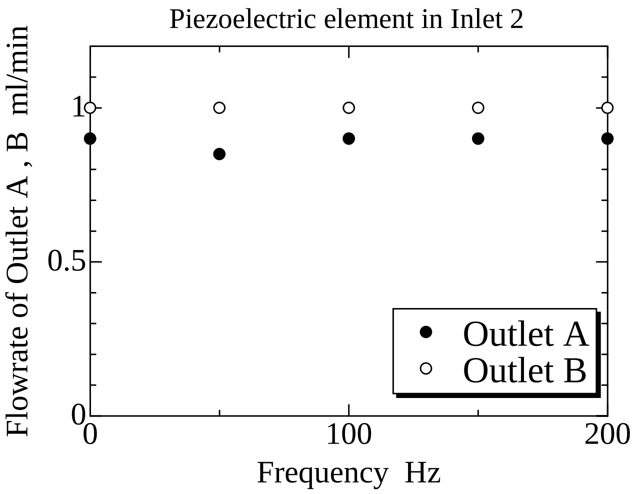


Fig. 13 Results of Integration of Mini/Micro-Size Y-Type Fluidic Device and Zero Net- Flow Micro-Jet (0.2 × 0.2 mm Cross-Section Test section)

CONCLUSIONS

Characteristics of a mini/micro-size Y-type fluidic device were examined using water as test fluid. The possibility of a zero-net flow micro-jet was experimentally examined. The new concept of the mini/micro-size fluidic device that has no actual signal port flow was proposed. Obtained conclusions are as follows.

1. Although Reynolds number tested was low; less than 1000, the mini/micro-size fluidic device functioned as a fluidic device; flow provided for a signal port flowed out from an opposite outlet. It was also analytically proved by the commercial code of STAR-CD.

2. A zero-net flow micro-jet which had been analytically predicted was experimentally confirmed.

3. A new concept of a mini/micro-size fluidic device was proposed. The signal ports were replaced with the zero-net flow micro-jet. A piezoelectric element was used to produce the zero-net flow micro-jet. It was confirmed that the new design would function as a fluidic device.

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